THE CAPABILITY OF THE MR DAMPER VERIFIED BY SHAKING TABLE TESTS AND REAL TIME HYBRID TESTS

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ABSTRACT :

Magnetorheological fluid damper (MR damper) has been expected to control the response of civil and building structures in recent years, because of its large force capacity and variable force characteristics. The important objective of this paper is to verify the validity of real-time hybrid tests by comparison with the test results of shaking table tests by using the same MR damper. The maximum damping force of the MR damper is 10 (kN), the stroke is 600(p-p) (mm), and the maximum piston velocity is 1(m/s). To determine the control force of the MR damper, optimal control theory and skyhook control were employed. The capability of the MR damper to control the response displacements and accelerations of base isolation system was verified by both shaking table tests and real-time hybrid tests. And then, the capability of the MR damper to control the response displacements and accelerations of base isolation system was verified by sliding mode control and $H\infty$ control.

KEYWORDS: Real time hybrid test, Semi active control, Shaking table test, MR damper

1. INTRODUCTION

Hybrid tests were developed, in order to make clear the behaviors of structures excited by earthquake ground motions. At first, pseudo-dynamic hybrid tests were conducted. Then, the method of real-time hybrid tests of passive structures was developed (Nakashima et al. 1992). On the other hand, researches of semi-active control using Mgnetorheological fluid damper (MR damper) have been developed (for example, Rabinow et al. 1948, Yoshioka et al. 2002, Fujitani et al. 2004). In the research of semi-active control there are three verification methods. One is the numerical simulation; the other one is the shaking table test. And the last one is the real-time hybrid test. In recent years, Christenson (Christenson et al. 2008), Wu (Wu et al. 2006), Carrion (Carrion et al. 2007) and Iemura et al. worked on the real-time hybrid test of semi-active control. Christenson et al. verify the accuracy of their method of real-time hybrid tests by numerical simulation. Wu et al. verify by spectrum radius analysis method. Authors conducted shaking table tests for base-isolation system and real-time hybrid tests by using same MR damper, in order to verify the accuracy of the real-time hybrid test (Fujitani et al. 2008).

2. OBJECTIVES

Authors have been worked on semi-active control of structures against earthquake ground motion, in order to improve the performance of the structure by using MR damper, not only to keep safety of human lives but also to keep function of buildings and comfort even in the duration of the ground motion (Fujitani et al. 2004). To verify the effectiveness of semi-active control, authors conducted shaking table tests. But the cost of shaking table tests is high, and many research institutes and university laboratories do not have shaking table. So, the system of real-time hybrid tests of semi-active control is eagerly longed. Kobe University developed a real-time hybrid test system, and the accuracy of the real-time hybrid test system was verified by comparing results of the test with results of shaking table tests in this paper.

3. TEST SPECIMEN

3.1. Magnetorheological (MR) damper

The maximum damping force of the MR damper used in this study is 10kN and its stroke is +/-300mm as shown in Table 1. Figure 2 shows the force-velocity relationship of the MR damper. The MR damper is modeled simply by the bingham plastic model as shown in Figure 3, and the relationship between the damper force and the electric current is approximated as Equation (1). Figure 4 shows the test results and simulated force-displacement relationship. The Bingham plastic model and Equation (1) shows good agreement between them.

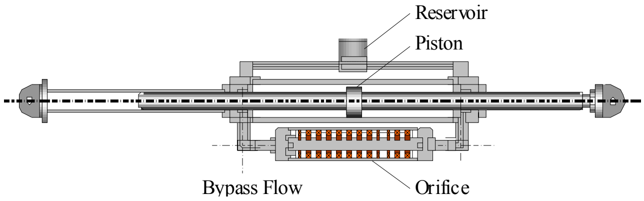


Figure 1 Structure of MR damper

Table 1 Dimensions of MR damper

Maximum Force		10 kN
Stroke		± 300 mm
Electromagnet	Max.Current	5.0 A
Magnetorheological fluid		Bando : ♯230

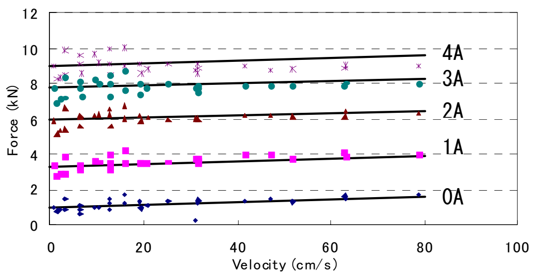


Figure 2 Force-piston velocity relationship of MR damper

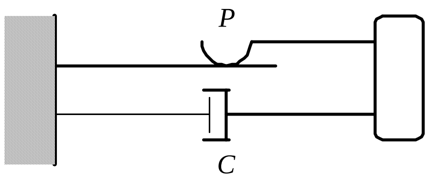
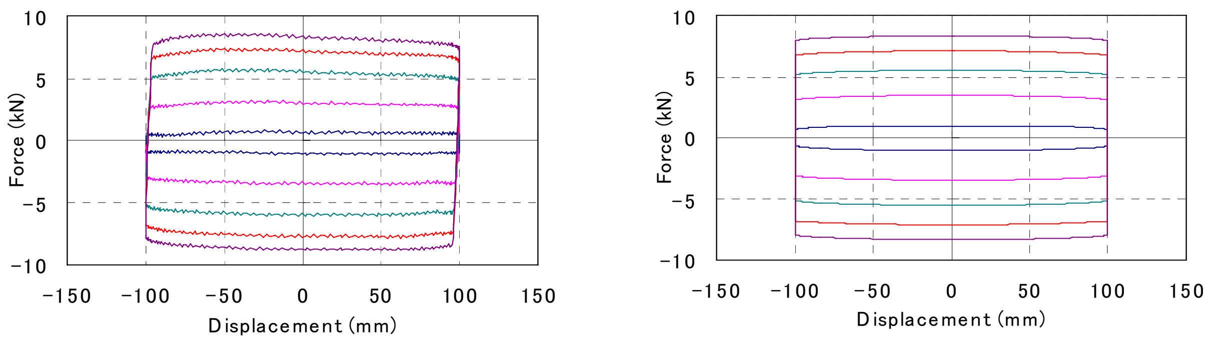


Figure 3 Bingham plastic model

$$F_{MR} = sign(v)(-219 \cdot I^2 + 2702 \cdot I + 611) + 1.90 \cdot v \quad (1)$$



(a) Test results (b) Simulated force-displacement relationship

Figure 4 Comparison of simulated force-displacement relationship and test results

3.2. Shaking table test specimen

The shaking table tests were conducted at Building Research Institute in Tsukuba, Japan. Figure 5 and Table 2 show the test specimen of base isolation system with one degree of freedom system. The test specimen was used, when optimal control was adopted. Figure 6 and Table 3 show the test specimen of base isolation system with two degrees of freedom system. The test specimen was used, when sky-hook control was adopted.

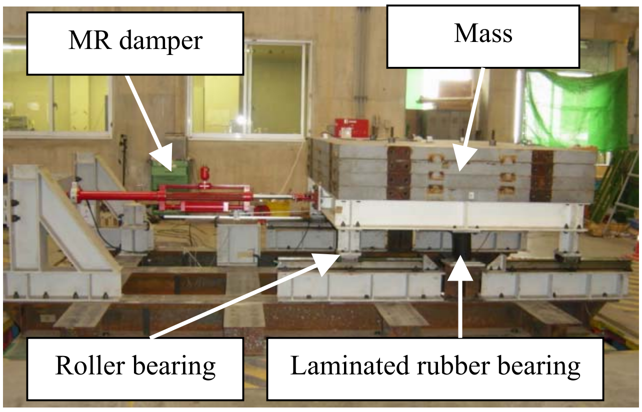


Figure 5 Testing system of base isolation (SDOF)

Table 2 Dimensions of testing system of SDOF

Mass / Weight	12.2	ton
Friction force of roller bearing	0.29	kN
Stiffness of laminated rubber bearing	51.1	kN/m
Damping coefficient	2.30	kN·s/m
Natural period	3.04	sec

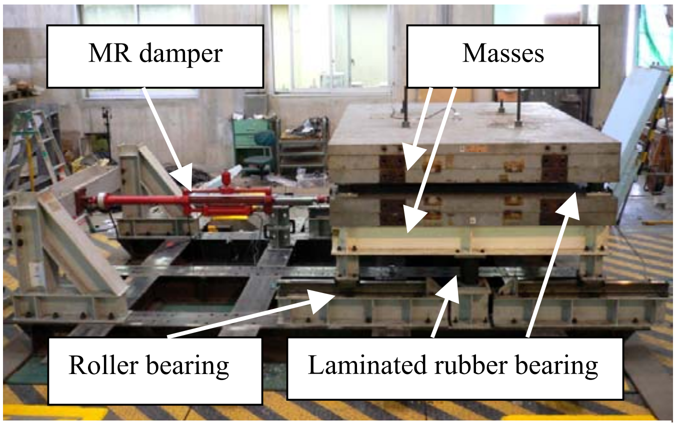


Figure 6 Testing system of base isolation (Two DOF)

Table 3 Dimensions of testing system (2DOF)

2nd floor

Mass / Weight	8.1	ton
Stiffness of laminated rubber bearing	3.5	kN/cm
Damping coefficient	0.03	kN·s/cm
Natural period	0.95	sec

Base-isolated layer

Mass / Weight	6.3	ton
Stiffness of laminated rubber bearing	0.5	kN/cm
Damping coefficient	0.03	kN·s/cm
Friction force of roller bearing	0.29	kN
Natural period	3.43	sec

4. REALTIME HYBRID TEST

A high velocity test machine with feed back control by DSP was set up in Kobe University (Figure 7). The maximum velocity is 1 (m/s), and the maximum force is 10 (kN) and the stroke is 600(p-p) (mm). The damper force is measured and input to DSP every 1/100 or 1/50 seconds. The response displacement and velocity are calculated by solving the equation of motion (differential equation) of the structure including the damper force, and the control variable (DC electric current, in case of MR damper) is calculated, too. The calculated response displacement and velocity are input to the test machine. The calculated control variable (DC electric current) is induced to the MR damper by electric power supply.

5. COMPARISON OF SHAKING TABLE TESTS AND REALTIME HYBRID TEST

Optimal control theory (Yang 1975) and skyhook control (Karnopp 1974) were adopted.

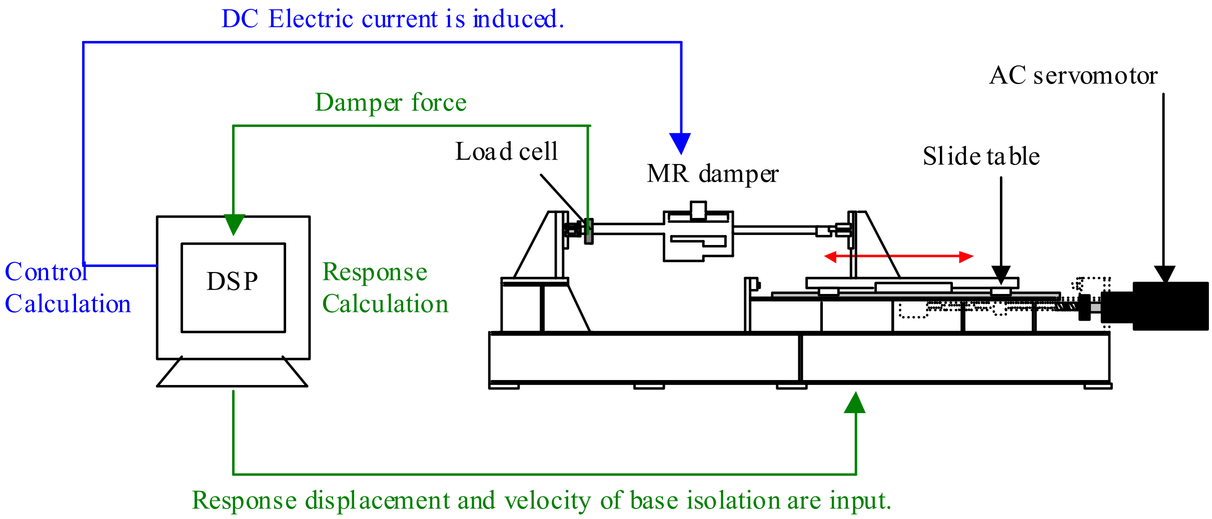


Figure 7 Real-time hybrid test system in Kobe University

5.1 *Optimal control*

In the case of the optimal control theory, authors apply the evaluation function shown in Equation (2).

$$J = \frac{1}{2}\int_0^{\infty}\left[\alpha_d x^2 + \alpha_v \dot{x}^2 + \alpha_a(\ddot{x}+\ddot{z})^2 + \gamma u^2\right]dt \tag{2}$$

α_d,α_v,α_a,γ are weighting coefficients, related to displacement, velocity, acceleration, control force. In this paper, α_d,α_v,α_a were fixed to 1,1,1 and γ was fixed to 0.01. The absolute acceleration, the relative displacement and the control force are shown in Figures 8.1-8.2. Against two kinds of earthquake ground motions (El Centro 1940 NS, JMA Kobe 1995 NS), acceleration, displacement and control force among shaking table test, hybrid test and simulation agree very well.

5.2 *Skyhook control*

The control force is generated by skyhook control theory, when the product of the absolute velocity and relative velocity is positive. The control force F(t) is decided by Equation (3).

$$|F(t)| = \lambda\sqrt{f(t)} \qquad (\lambda = 1) \tag{3}$$

$$f(t) = \frac{1}{2}m\dot{u}_t^2 + \frac{1}{2}ku_t^2 \tag{4}$$

$f(t)$: sum of kinetic energy and strain energy (kJ), m : mass of superstructure (t),

k : stiffness of base isolation layer (kN/m), u_t , $\dot{u}_t$: displacement (m) and velocity (m/s) of superstructure

The absolute accelerations of each mass, the relative displacements of each story, the induced electric current and the control force are shown in Figures 9. Against the earthquake ground motions of El Centro 1940 NS. Acceleration of each story, displacement of each story, electric current and control force among shaking table test, hybrid test and simulation agree very well.

6. APPLICATION OF REALTIME HYBRID TEST

6.1 *Sliding mode control (SMC)*

The state equation and switching function of a structure are represented by Equation (5).

$$\begin{cases}\dot{X} = AX + Bu \\ \sigma = SX = 0\end{cases} \tag{5}$$

First, S, which represents the inclination of the hyper plane, is selected as the feedback gain of optimum control as shown in Equation (6).

$$S = R^{-1}B^{T}P \tag{6}$$

P is a solution of the Riccati equation as shown in Equation (7)

$$\begin{aligned} &PA_{\varepsilon} + A_{\varepsilon}^{T}P - PBR^{-1}B^{T}P + Q = 0 \\ &A_{\varepsilon} = A + \varepsilon I(\varepsilon \geq 0) \end{aligned} \tag{7}$$

For the switching control rule, the eventual sliding mode control scheme is used. Controlling force u is given by Equation (8).

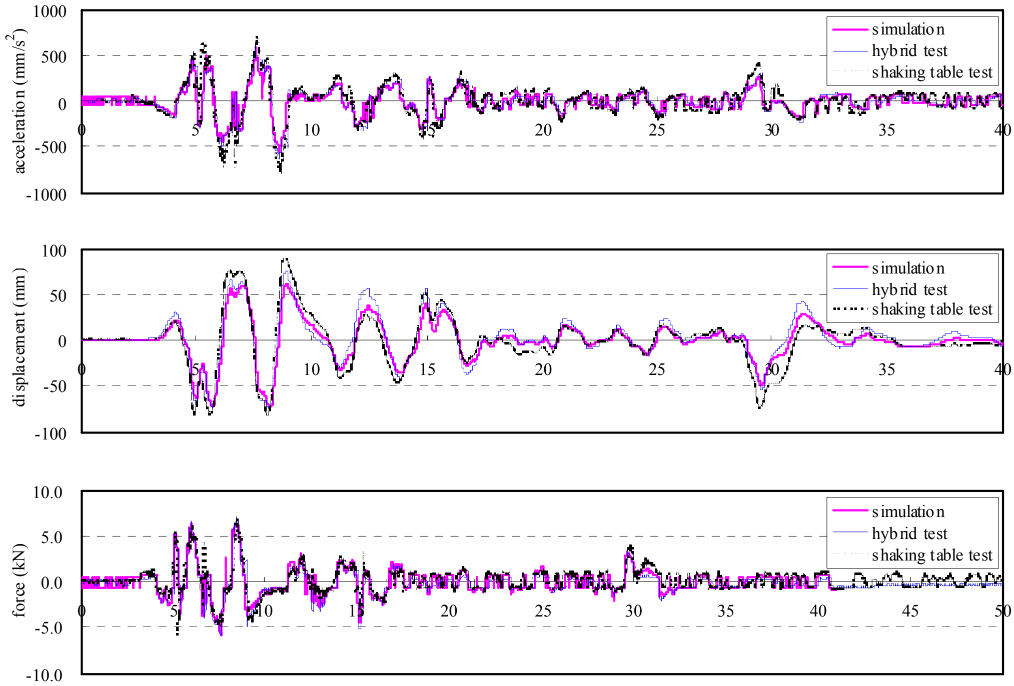


Figure 8.1 Comparison of hybrid test, shaking table test and numerical simulation in case of El Centro 1940 NS

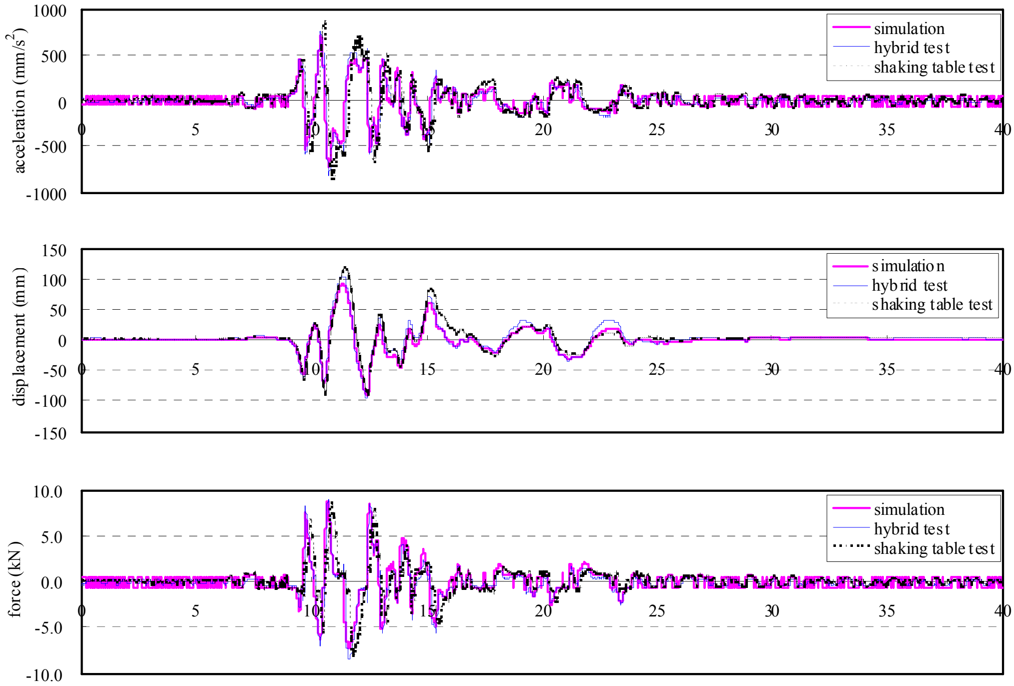


Figure 8.2 Comparison of hybrid test, shaking table test and numerical simulation in case of JMA Kobe 1995 NS

$$u = -(SB)^{-1} SAX - \eta \frac{\sigma}{\|\sigma\| + \gamma} \tag{8}$$

Lyapunov function V is selected as shown in Equation (9), and η is obtained so that its first-order differential becomes negative.

$$\begin{cases} V = 0.5\sigma^2 \\ \dot{V} < 0 \end{cases} \tag{9}$$

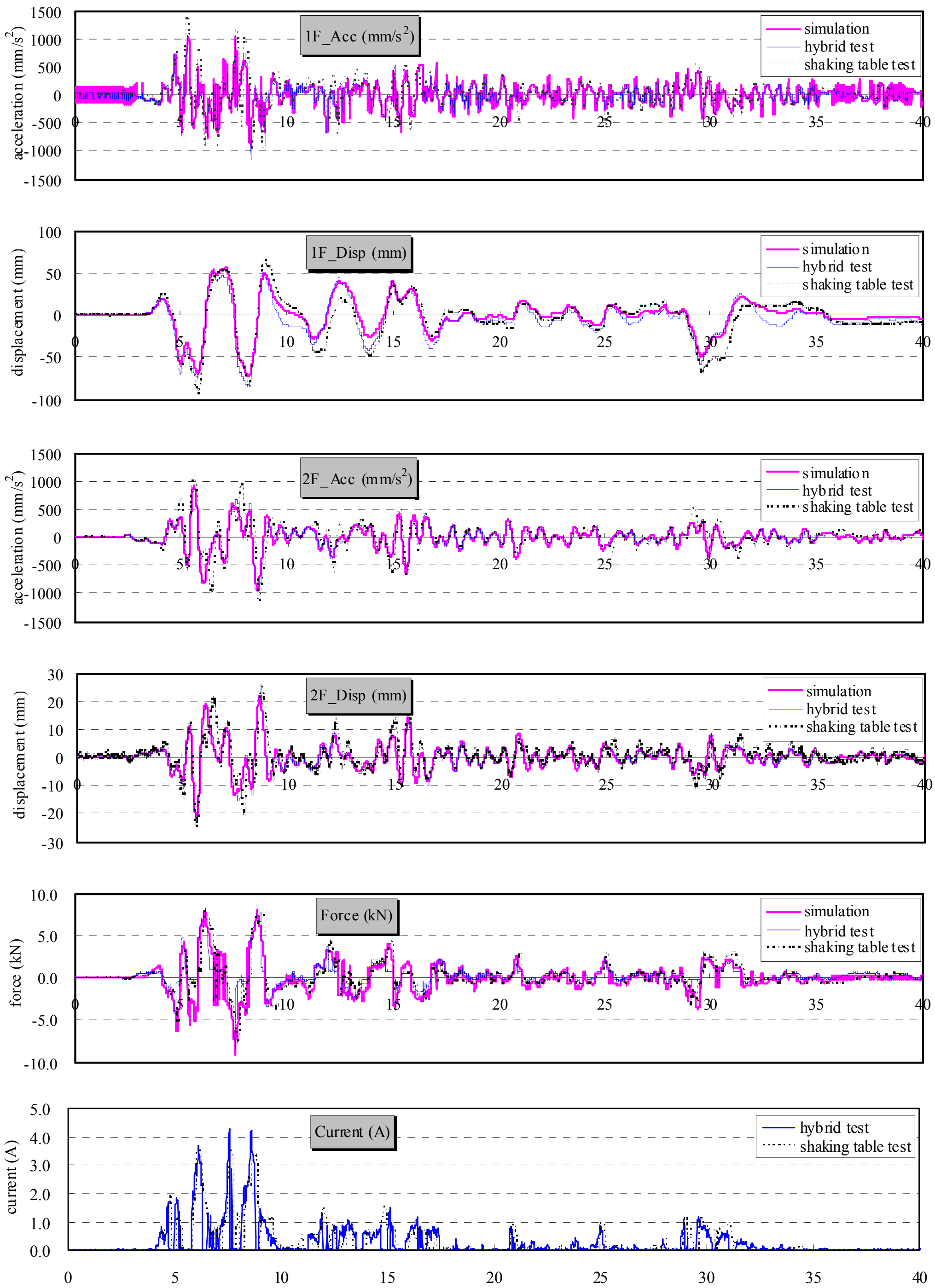


Figure 9 Comparison of hybrid test, shaking table test and numerical simulation in case of El Centro 1940 NS

SMC and some control methods were applied to single-degree-of-freedom system shown in Figure 10 and Table 4; a comparative study of the response suppression performances of SMC was performed. Comparison of the absolute acceleration and response displacement at SMC and at non-control state, time-history of controlling force of SMC are shown in Figure 11. El Centro 1940 NS was used as the input earthquake ground motion. The test results of following cases were compared.

Case 1) No damper
Case 2) Passive control when constant electric current is applied
(0, 0.5, 1, 1.5, 2, 3, 4 (A))
Case 3) Passive control by constant damping coefficient
(10, 20, 30, 50, 100 (kNs/m))
Case 4) Semi-active control by optimal control theory
Case 5) Semi-active control by Sliding Mode Control

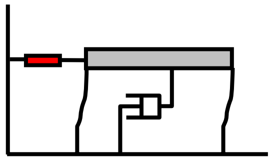


Figure 10 Single degree of freedom system

Table 4 Characteristics of the system

Mass (kg)	6000
Stiffness (kN/m)	240
Damping factor	0.02
Natural period (s)	0.994

Figure 11 shows the relationship between the maximum displacement and maximum absolute acceleration. Both the maximum displacement and the maximum absolute acceleration were reduced to about one-fourth by SMC compared to those uncontrolled. Furthermore, the maximum displacement was nearly equal to the minimum value by another control method; the maximum acceleration was about one-half, which revealed that SMC reduced both displacement and acceleration.

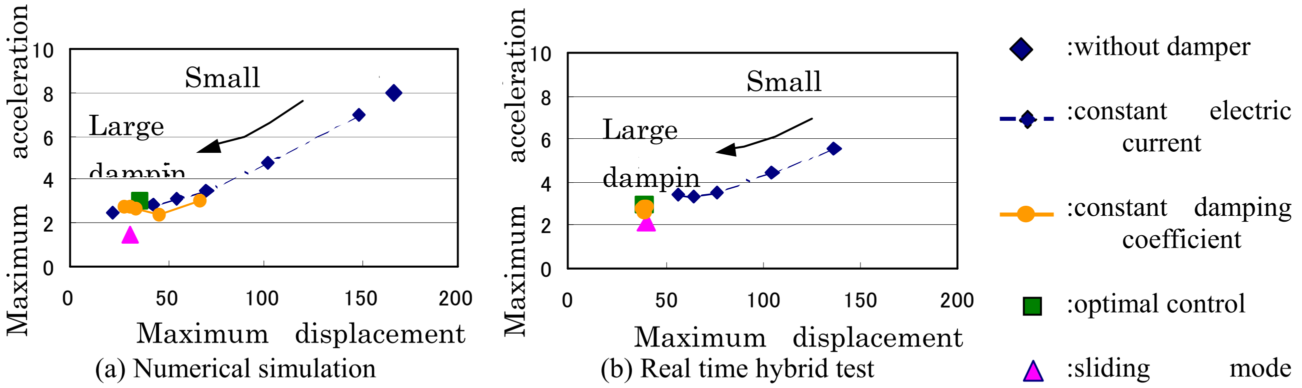


Figure 11 Relationship of maximum displacement and maximum acceleration

6.2 *H∞ Control*

The real-time hybrid test system was applied to a single degree of freedom system by using H∞ Control. Although the control system designed to the natural period of T=1.0 (s), the actual natural period Ta may be 0.8 (s) or 1.2 (s). The results are shown in Table 5 (acceleration) and Table 6 (displacement). In case of Ta=0.8, the reduction ratio became worse a little than the case of Ta=1.0. On the other hand, in case of Ta=1.2, the reduction ratio was almost same as case of Ta=1.0.

7. CONCLUSIONS

A real-time hybrid test system was developed for the test of semi-active control in Kobe University, and the accuracy of the system was verified by comparing results of the test with results of shaking table tests in this paper. Base-isolated structure was controlled by optimal control theory. And Application by using sliding mode control and H∞Control were introduced.

ACKNOWLEDGEMENT

The authors wish to thank to Dr. Taiki Saito and Mr. Namihiko Inoue of Building Research Institute.

Table 5 Comparison of the maximum absolute acceleration of real-time hybrid test and simulation

El Centro-NS	max. absolute acceleration			
	simulation		real time hybrid test	
Ta=0.8 (designed T=1.0)	0A	H∞control	0A	H∞control
max. absolute acceleration (mm/s2)	5460	4846	5713	5210
reduction ratio (%)	–	11.3	–	8.8
accelaration RMS value (mm/s2)	1406	1044	1547	1174
Ta=1.0 (designed T=1.0)	0A	H∞control	0A	H∞control
max. absolute acceleration (mm/s2)	4943	3212	5357	3450
reduction ratio (%)	–	35.0	–	35.6
accelaration RMS value (mm/s2)	1048	721	1151	812
Ta=1.2 (designed T=1.0)	0A	H∞control	0A	H∞control
max. absolute acceleration (mm/s2)	2937	1888	3271	2051
reduction ratio (%)	–	35.7	–	37.3
accelaration RMS value (mm/s2)	834	510	970	568

Table 6 Comparison of the maximum displacement of real-time hybrid test and simulation

El Centro-NS	max. displacement			
	simulation		real time hybrid test	
Ta=0.8 (designed T=1.0)	0A	H∞control	0A	H∞control
max. displacement (mm)	87.1	72.2	91.6	76.8
reduction ratio (%)	–	17.1	–	16.2
Ta=1.0 (designed T=1.0)	0A	H∞control	0A	H∞control
max. displacement (mm)	123.2	73.9	134.0	78.0
reductiion ratio (%)	–	40.0	–	41.8
Ta=1.2 (designed T=1.0)	0A	H∞control	0A	H∞control
max. displacement (mm)	104.6	63.8	117.2	67.5
reduction ratio (%)	–	39.0	–	42.4

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